Digital Elevation Models of Southern Louisiana:
Procedures, Data Sources and Analysis

Prepared for the Hurricane Forecast Improvement Project (HFIP) by
NOAA National Geophysical Data Center (NGDC)
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Contents

List of Figures

List of Tables

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1 INTRODUCTION

Modeling and mapping of coastal processes (e.g. tsunamis, hurricane storm-surge, and sea-level rise) requires digital representations of Earth's solid surface, referred to as digital elevation models (DEMs). Some modeling utilizes structured, square-cell DEMs, while others utilize unstructured DEMs that have no regular cell size or pattern. Usually, these different DEM types are developed independently, even though they are built from the same source bathymetric and topographic datasets. The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two bathymetric-topographic structured DEMs and two bathymetric-topographic unstructured DEMs of southern Louisiana (Figure 1). The DEMs were developed for the Hurricane Forecast Improvement Project (HFIP), with the purpose of developing a new methodology for building companion structured and unstructured DEMs. The Southern Louisiana DEMs were constructed to meet the Coastal Survey Development Lab (CSDL) specifications (Tables 1 and 2), based on storm surge and sea level rise modeling requirements.

The 1/3 arc-second structured DEM[1] referenced to North American Vertical Datum of 1988 (NAVD 88) was carefully developed and evaluated. The source bathymetric and topographic datasets used in the development of the structured DEMs were utilized along with the final NAVD 88 DEM to develop the unstructured DEMs. A NAVD 88 to mean high water (MHW) 1/3 arc-second conversion grid, derived from VDatum project areas, was created to model the relationship between NAVD 88 and MHW in the southern Louisiana region. NGDC combined the NAVD 88 DEM and the conversion grid to develop a 1/3 arc-second MHW structured DEM and sampled the vector nodes of the final unstructured NAVD 88 DEM to the conversion grid to generate a MHW unstructured DEM. The DEMs were generated from diverse digital datasets in the region (grid boundary and sources shown in Figures 1, 4 and 6). The DEMs were developed to be used for storm surge inundation and sea level rise modeling. This report provides a summary of the data sources and methodology used in developing the four Southern Louisiana DEMs.

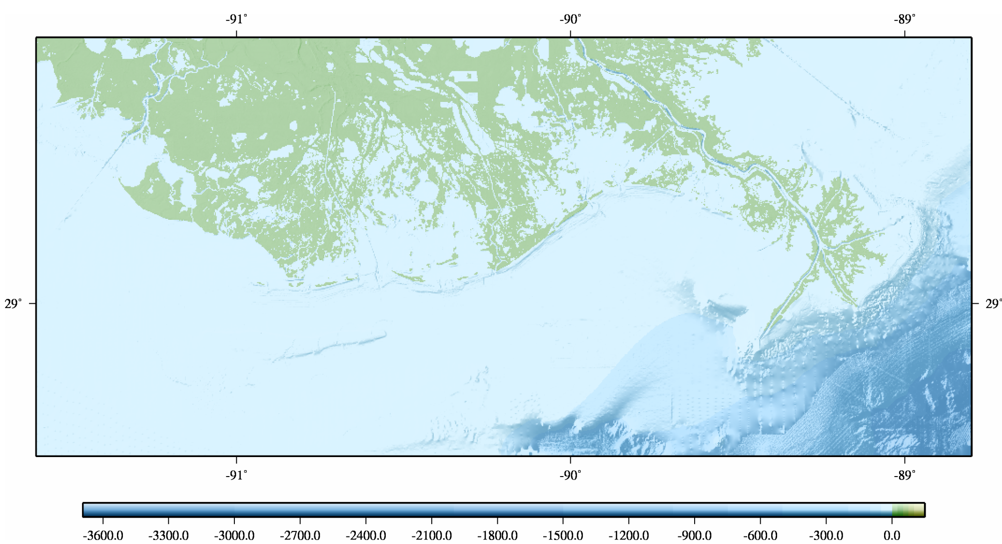


Figure 1: *Shaded relief image of the Southern Louisiana NAVD 88 structured DEM*

[1]The Southern Louisiana DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Empire, LA, 1/3 arc-second of latitude is equivalent to 10.2641 meters; 1/3 arc-second of longitude equals 8.9371 meters

2 Study Area

The Southern Louisiana DEMs cover the area south of the City of New Orleans, Louisiana and west to St. Mary Parish, Louisiana. The Southern Louisiana DEMs consist of portions of seven Louisiana parishes (St. Bernard, Plaquemines, Jefferson, St. Charles, Ascension, St. Mary, Terrebonne) (Figure 2). The southern Louisiana region contains some of the fastest changing landscape in the world. The Atchafalaya delta is quickly growing due to higher quantities of silt and clay deposits from the Atchafalaya River, while much of the rest of the coast in Lafource and Terrebone parishes is receding due to erosion and subsidence causing the loss of land.

Table 1: Specifications for the Southern Louisiana Structured DEMs

Grid Area	Southern Louisiana
Coverage Area	3810 ° 19.42.35' N, 7510 ° 6.3111' W
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	North American Vertical Datum of 1983 (NAVD 88)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

Table 2: Specifications for the Southern Louisiana Unstructured DEMs

Grid Area	Southern Louisiana
Coverage Area	3810 ° 19.42.35' N, 7510 ° 6.3111' W
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	North American Vertical Datum of 1983 (NAVD 88)
Vertical Units	Meters
Grid Spacing	Variable
Grid Format	ESRI Shapefile
Minimum Angle	20 Degrees

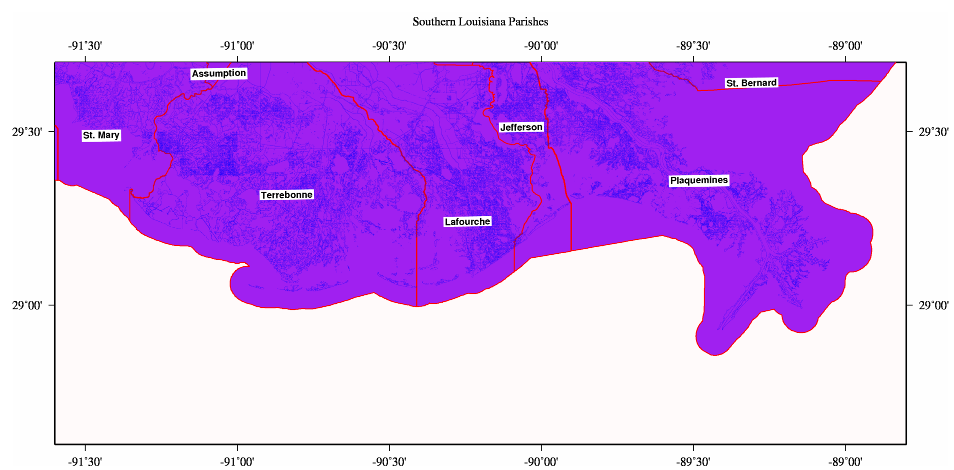


Figure 2: *Extents of the Southern Louisiana project area and the parishes located within*

3 SOURCE ELEVATION DATA

The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum 1983 (NAD 83)[2] and mean high water (MHW), for modeling of maximum flooding, respectively. Data were gathered in an area slightly larger (∼5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

3.1 Data Sources And Processing

Coastline, bathymetric, and topographic digital datasets (Tables 3, 4, and 5) were obtained from several U.S. federal agencies: NOAAs NGDC, Office of Coast Survey (OCS) and Coastal Services Center (CSC); the U.S. Geological Survey (USGS); and the U.S. Army Corps of Engineers (USACE). Safe Softwares FME data translation tool package was used to shift datasets to NAD 83 horizontal datum. The datasets were then displayed with ESRIs ArcGIS, ESRI Imagery World 2D Online World Imagery 2D, and Applied Imagerys Quick Terrain Modeler software (QT Modeler) to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using NOAAs Vertical Datum Transformation (VDatum)[3] software, FME, and ArcGIS, based upon data from NOAA tide stations (see Section 3.2.1).

3.1.1 Coastline

Coastline datasets of the Southern Louisiana region were obtained from a variety of sources. The main dataset used in developing a combined, detailed coastline was the hydro-breakline dataset distributed through the Louisiana State University (LSU) Atlas GIS (Table 3, Figure 3). This dataset provided a detailed NAVD 88 coastline of much of the Southern Louisiana DEM coverage area. NGDC evaluated but did not use the NOAA Office of Coast Survey (OCS) coastline.

For areas not included in the detailed hydro-breaklines, a detailed coastline was digitized by NGDC using aerial imagery. The digitized coastline was assumed to be drawn to the MHW coastline, and consists almost entirely of marsh-land.

Table 3: Shoreline Datasets Used in Compiling the Southern Louisiana DEMs

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
LSU	1999	Composite vectorized hydrolic breaklines	Not defined	NAD 83 geographic	NAVD 88	http://atlas.lsu.edu/rasterdown.htm
NGDC	2010	Digitized vector Coastline	Not defined	WGS 84 geographic	MHW	N/A

[2]The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

[3]VDatum is a free software tool being developed jointly by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS). VDatum is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums.

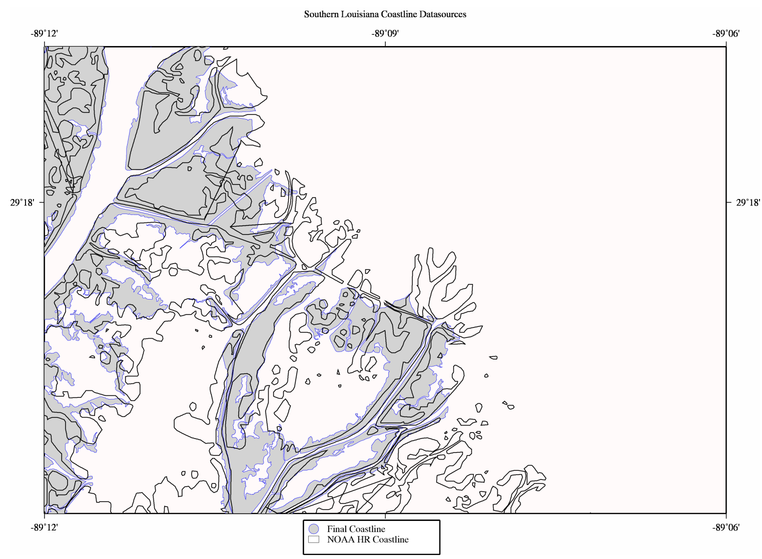


Figure 3: *Portion of hydro-breakline and other coastline datasets in the Southern Louisiana DEM.*

3.1.2 Bathymetry

Bathymetric datasets available in the Southern Louisiana region included 89 National Ocean Service (NOS) hydrographic surveys, six NOS high-resolution hydrographic surveys in Bathymetric Attributed Grid (BAG) format, nine United States Army Corps of Engineers (USACE) hydrographic surveys of dredged channels and cross sections of lakes, and 14 Electronic Nautical Charts (ENC) that were available from OCS (Table 4; Figure 4). NGDC evaluated but did not use the multibeam surveys acquired from the NGDC multibeam database due to quality issues.

See Sections 3.2.1 and 3.2.2 for horizontal and vertical datum transformation specifics, respectively.

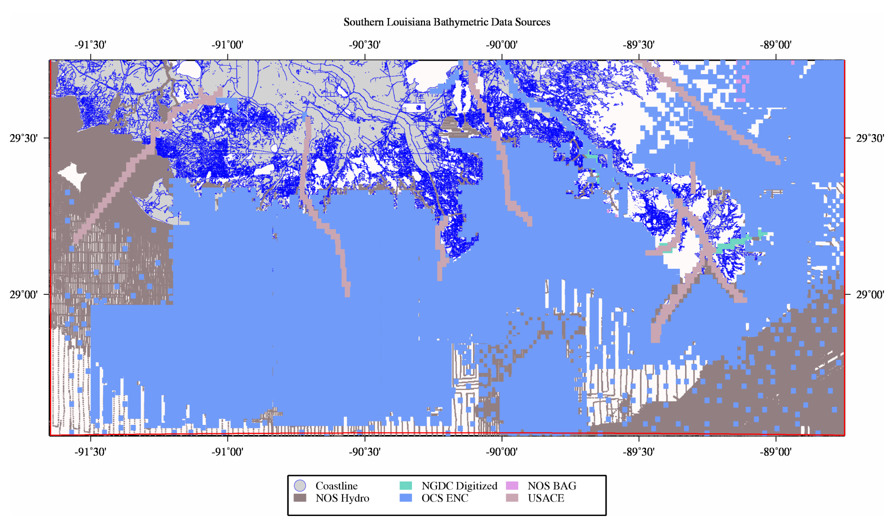


Figure 4: *Bathymetric data sources in the Southern Louisiana region.*

1. **NOS Hydrographic Surveys**
   A total of 89 NOS hydrographic surveys conducted between 1876 and 2003 were available for use in the development of the Southern Louisiana DEMs (Figure 5a, Table B-2). CSDL provided NGDC with a non-superceded database of NOS hydrographic surveys. The database excluded NOS survey data if there were more recent NOS

Table 4: Bathymetric Datasets Used in Compiling the Southern Louisiana DEMs

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
NOS-CSDL	1876 to 2003	Hydrographic Survey Soundings	Ranges from 1:5,000 to 1:80,000	NAD 83 geographic	MLLW or MLW	http://www.nauticalcharts.noaa.gov/csdl/welcome.htm
NOS-OCS-HSD	2007	High resolution hydrographic survey soyundings	n/a	NAD 83 UTM Zone 16N	MLLW	http://www.ngdc.noaa.gov/ngdc.html
USACE New Orleans District	2009	Hydrographic survey soundings	Line spacing ranging from 60 to 120 m apart and point spacing 5 to 10 m	NAD 83 Louisiana State Plane (feet)	MLG/MLLW (feet)	http://www.mvn.usace.army.mil
NGDC	2010	Digitized soundings	N/A	NAD 83 geographic	NAVD 88	N/A
OCS	2010	Extracted points from ENC	Ranges from 1:20,000 to 1:458,596 (varies by chart)	WGS84 geographic	MLLW	http://www.nauticalcharts.noaa.gov

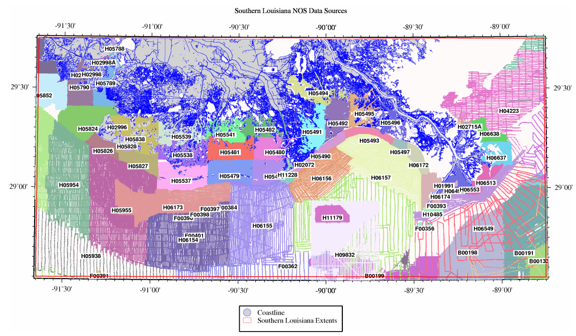
survey data at the same location. NGDC also manually edited older NOS hydrographic survey data that were inconsistent with USACE soundings in more recently dredged channels. The data were vertically referenced to mean lower low water (MLLW) or mean low water (MLW) and horizontally referenced to NAD 83 geographic. Survey data were used in an area 0.05 degree (∼5%) larger than the Southern Louisiana DEM extent to support data interpolation across grid edges. Data point spacing for the NOS surveys varies by collection date. In general, earlier surveys had greater point spacing than more recent surveys. NOS survey data were transformed from MLLW or MLW to NAVD 88 using VDatum. The data were displayed in Earth Systems Research Institute (ESRI) ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to the various topographic and bathymetric data, the final coastline, and OCS Raster Navigational Charts (RNCs). Six additional NOS high-resolution hydrographic surveys, in BAG format, were conducted between 2007 and 2008 and were available for use in the development of the Southern Louisiana DEM (Figure 5b, Table B-2).

2. **USACE hydrographic surveys**
   Nine USACE bathymetric survey projects located at least partially within the Southern Louisiana DEM extent were downloaded from the USACE New Orleans District web site in Design (DGN) or ascii *xyz* format (Figure 5c, Table B-3). NGDC used the Geographic Data Abstraction Layer (GDAL) ogr2ogr tool to extract *xyz* data from the DGN files. Several DGN files lacked corresponding *xyz* data. NGDC digitized the missing sections of the dredged channels to ensure their representation in the DEM (Figure 5d). The surveys were collected between 2008 and 2010, and were referenced to NAD 83 Louisiana State Plane (feet) and mean low gulf (MLG) datums. Surveys consist of numerous, parallel, across-channel profiles, spaced 50 to 350 meters apart, with point soundings 5 to 10 meters apart.

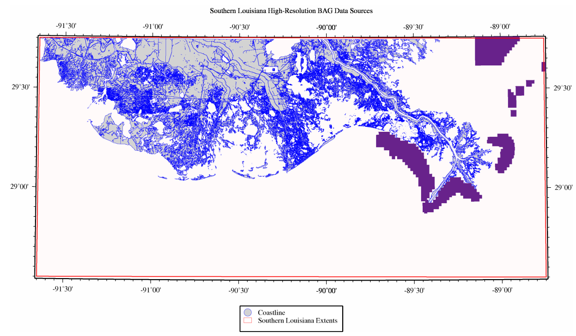
3. **NGDC Digitized Soundings**
   NGDC used the Geophysical Data System (GEODAS) Hydro-Plot program to digitize bathymetric soundings in estuary rivers and dredge channels. NGDC interpolated bathymetric soundings at 10 meter spacing based on available bathymetric soundings and OCS RNCs. Interpolated soundings were created in estuary rivers and

dredged channels to more accurately model channel morphology where there were no NOS hydrographic survey soundings or the NOS soundings' point spacing were significantly greater than 10 meters (Figure 5d).

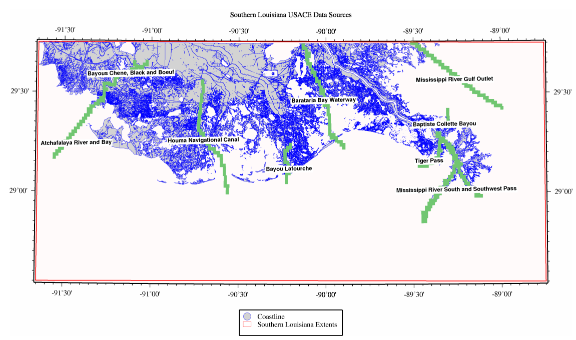
4. **OCS Electronic Navigational Charts**
   Fourteen ENCs were available from OCS in the Southern Louisiana coverage area (Figure 5e, Table B-4). The ENCs were downloaded from the OCS web site, and were horizontally referenced to NAD 83 geographic and vertically referenced to MLLW. The data were reviewed and compared to the coastline and to the corresponding RNCs.



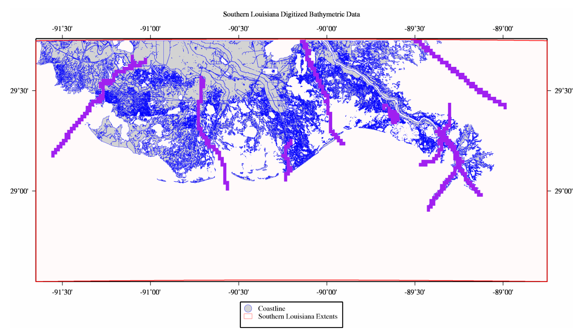
(a) *NOS digital hydrographic survey coverage in the Southern Louisiana region. Some soundings from earlier surveys were not used as they have been superseded by more recent surveys.*



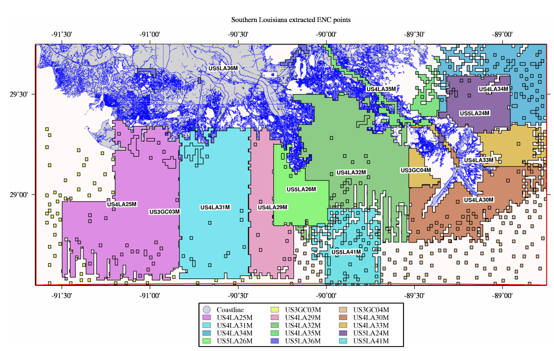
(b) *High resolution NOS hydrographic data coverage in the Southern Louisiana region.*



(c) *USACE hydrographic data coverage in the Southern Louisiana region.*



(d) *NGDC HydroPlot digitization coverage in the Southern Louisiana region.*



(e) *OCS/ENC bathymetric datasets available in the northern Gulf Coast region.*

Figure 5: *Bathymetric data sources in the southern Louisiana region.*

3.1.3 Topography

The topographic datasets used to build the Southern Louisiana DEMs include: State of Louisiana lidar; CSC Post Katrina Topo/Bathy Lidar; CSC Post Katrina Levees lidar; CSC USGS ATM lidar; and CSC Fall-GC lidar (Table 5; Fig. 6). NGDC evaluated but did not use the United States Geological Survey (USGS) National Elevation Dataset (NED) 1, NED 1/3 or NED 1/9th arc-second DEM due to the poor quality of data, particularly in marshy low-lying areas.

See Sections 3.2.1 and 3.2.2 for horizontal and vertical datum transformation specifics, respectively.

Table 5: Topographic Datasets Used in Compiling the southern Louisiana DEMs

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Coordinate System*	*URL*
LSU	1999	Bare-earth lidar	1 - 5 meters	UTM Zone 15 N	NAVD 88 GEOID 2009 Feet	http://atlas.lsu.edu/lidar/
CSC	2005	Non Bare-earth lidar	1 - 5 meters	WGS 84 geographic	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html
CSC	2005	Non Bare-earth Levees lidar	1 - 5 meters	WGS 84 geographic	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html
CSC	2005	Bare-earth merged lidar	1 - 5 meters	UTM Zone 15 N	NAVD 88	http://webqa.csc.noaa.gov/digitalcoast/data/coastallidar/index.html
NGDC	2010	Digitized elevations	Unknown	WGS 84 geographic	NAVD 88	N/A

1. **State of Louisiana Lidar**
   Topographic lidar of the State of Louisiana was collected by 3001 Inc. in 2003 for the USACE, St. Louis District (Figure 7a). The data were provided by LSU Atlas GIS as ascii Comma Separated Value (csv) files and were horizontally referenced to NAD 83 Universal Transverse Mercator (UTM) Zone 15N, and vertically referenced to NAVD 88 GEOID 1999. The assessed vertical accuracy was 17.44 cm average Root Mean Square Error (RMSE)[4], while the horizontal accuracy was not assessed.

2. **CSC Post-Katrina levee lidar**
   Helicopter-mounted topographic lidar data were collected for USACE over the New Orleans Hurricane Protection Levee System (NOHPLS) in Louisiana following Hurricane Katrina (Figure 7b). The horizontal and vertical accuracies of this dataset was not assessed. These data were collected for the assessment of Hurricane Katrina's damage to the hurricane protection levees. Users should be aware that the data depict the heights at the time of the survey and are only accurate for that time. Users should not use this data for critical applications without a full awareness of its limitations. This dataset was retrieved horizontally referenced to WGS 84 geographic and vertically referenced to NAVD 88.

3. **CSC Fall Gulf Coast lidar**
   The Airborne LiDAR Assessment of Coastal Erosion (ALACE) project was a partnership between NOAA,

[4] Root Mean Square Error (RMSE) is defined as: $\sum_{i=1}^{n} \frac{(x_1,i - x_2,i)^2}{n}$

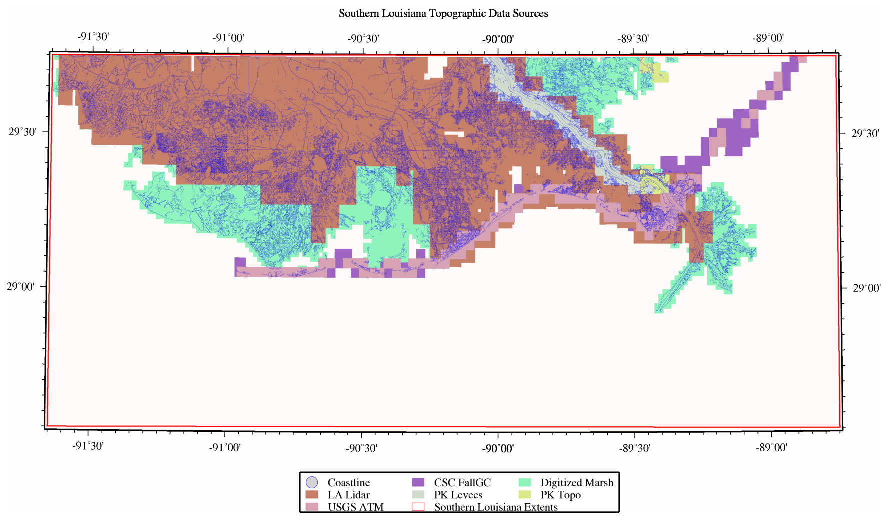


Figure 6: *Topographic data sources in the Southern Louisiana region.*

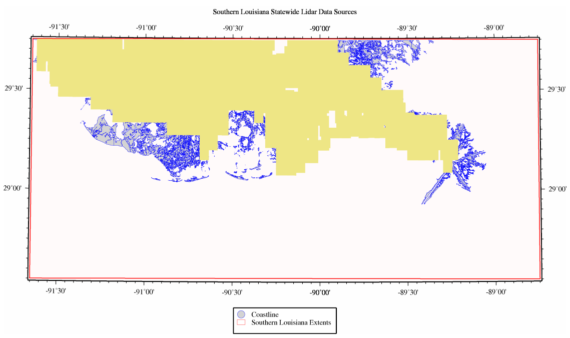
NASA, and U.S. Geological Survery (USGS). Participants in the project have been collecting baseline coastal topographic data for the conterminous U.S. since 1996. NOAA left the partnership after the fall 2000 season, but USGS and NASA continue to collect data for research purposes. This data may eventually be available via LDART. The ALACE collections are typically targeted at a narrow strip of sandy beach and are usually a kilometer or less in width. Many areas have both baseline data and post-storm data. In general, this data has not been checked with ground control, but has undergone internal consistency checks. The acquisition of baseline coastal topographic data primarily occurs during the fall, prior to winter erosion and when the beach is generally at its widest due to sand accumulation over the summer months. However, research missions are also conducted at other times to study the coastal impacts of weather phenomena such as El Nino or hurricanes. All flights are timed to occur within a few hours of low tide, when the beach is most exposed. This dataset was retrieved horizontally referenced to WGS 84 geographic and vertically referenced to NAVD 88. A portion of this dataset was used in the development of the southern Louisiana DEMs (Figure 7c).

4. **CSC Topo/Bathy Coastal lidar**
   The lidar-derived data were collected by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The data includes hydrographic and topographic data. The data were collected to depict the elevations above and below water along the immediate coastal zone. The survey generally extends 750 meters inland and up to 1500 meters over the water (depending on water depth and clarity). The goal of the project was to collect data covering the shoreline of the conterminous United States where feasible. The project was led by the U.S. Army Corps of Engineers. The assessed vertical accuracy of this dataset was 0.20 meters at 1 sigma. This dataset was evaluated and portions were used for the development of the Southern Louisiana DEM (Figure 7d) to better model levees where no other data were available. The entire dataset was not used in the development of the Southern Louisiana DEM due to the fact that the dataset was not filtered to bare earth. This dataset was retrieved horizontally referenced to WGS 84 geographic and vertically referenced to NAVD 88.

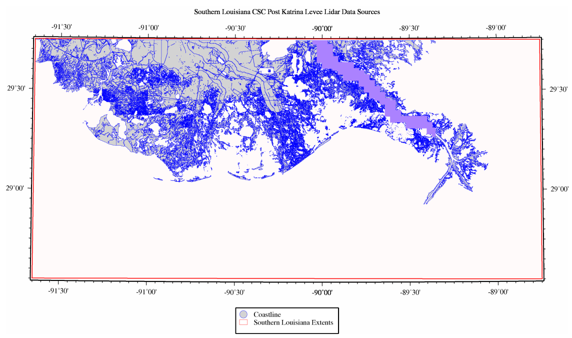
5. **CSC USGS ATM Lidar**
   The Decision Support for Coastal Science and Management project, sponsored by the USGS Coastal and Marine Geology Program (CMGP), is supporting the creation of new capabilities for the synoptic remote sensing of coastal-marine and terrestrial environments based on aircraft and satellite sensors. These coastal remote-sensing, mapping, and point-monitoring tools constitute a unique integrated package of instrumentation and software that may be deployed in support of appropriately timed and scaled zoning decisions by management authorities in order to conserve and sensibly exploit nearshore coastal and marine ecosystems.This project provides highly detailed and accurate topography datasets to natural-resource managers and research scientists for use as a man-

agement tool. The Experimental Advanced Airborne Research Lidar (EAARL) system, originally developed at the NASA Wallops Flight Facility in Virginia, is used to map near-shore bathymetry, topography, and vegetation structure simultaneously. The EAARL is a green-wavelength, waveform-resolving airborne lidar system specifically designed to measure submerged topography and adjacent coastal land elevations seamlessly in a single scan of transmitted laser pulses. The resulting data from the collected elevation measurements are processed using the Airborne Lidar Processing System (ALPS), which is a custom-built processing system developed in a NASA-USGS collaboration, and published as a USGS Open-File Report or Data Series. Further information about the project, EAARL system, and USGS publications is available at http://ngom.usgs.gov/dsp/. This dataset was retrieved horizontally referenced to WGS 84 geographic and vertically referenced to NAVD 88. A portion of this dataset was used in the development of the southern Louisiana DEMs (Figure 7e).

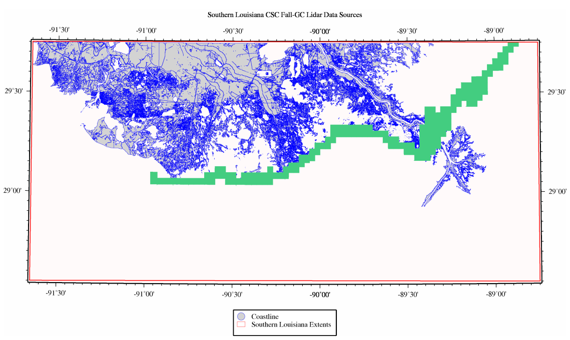
6. **NGDC Digitized elevations**
   The NGDC digitized topography in areas of marshland and swamp (Figure 7f) primarily in Plaquemines, St. Bernard, Lafourche, and Jefferson parishes. Available USGS NED topographic data for this region were determined to be of poor quality and were not used. NGDC utilized NAVD 88 to MHW conversion grid, nearby known elevation values, and satellite imagery to determine the elevation values of the marshes and swamps. The vertical accuracy of this dataset has not been determined.



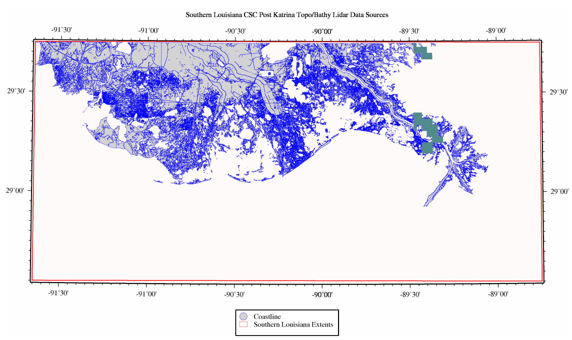
(a) *Louisiana lidar data extents used in the Southern Louisiana DEM*



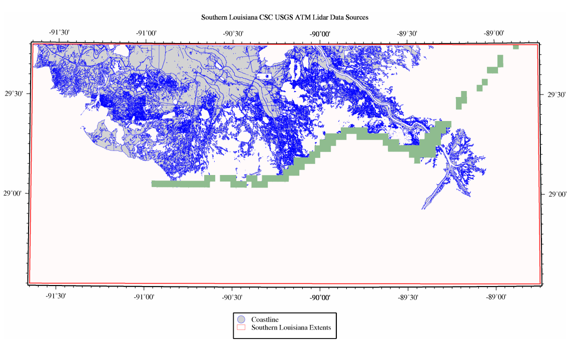
(b) *CSC Post Katrina Levee Lidar data used in the Southern Louisiana DEM.*



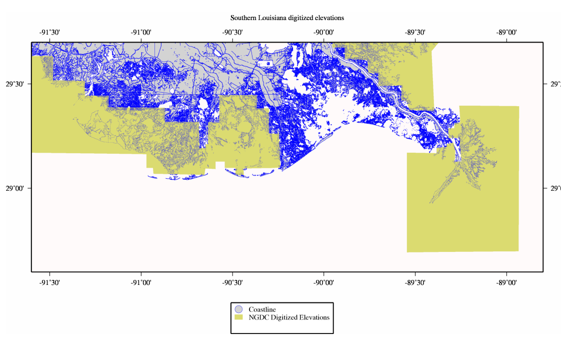
(c) *CSC Fall Gulf Coast data used in the Southern Louisiana DEM.*



(d) *Portion of CSC coastal lidar used in the development of the Southern Louisiana NAVD 88 DEM*



(e) *CSC USGS ATM Lidar dataset used in the Southern Louisiana NAVD 88 DEM*



(f) *NGDC digitized elevations used in the Southern Louisiana DEM.*

Figure 7: *Topographic datasets available in the southern Louisiana region.*

3.2 Establishing Common Datums

3.2.1 Vertical Datum Transformations

Datasets used in the compilation and evaluation of the Southern Louisiana DEMs were originally referenced to several vertical datums including MLLW, MLW, MLG and NAVD 88. All datasets were transformed to NAVD 88 using VDatum.

- **Bathymetric Data** All hydrographic surveys were transformed from MLLW, MLW or MLG to NAVD 88, using VDatum.
- **Topographic Data** All topographic datasets used in the compilation of the Southern Louisiana DEMs originated in NAVD 88 vertical datum. No further vertical transformations were required for these datasets. Vertical transformations of the Louisiana lidar dataset were performed to increase the accuracy of the dataset.[5]

3.2.2 Horizontal Datum Transformations

Datasets used to build the Southern Louisiana DEMs were downloaded or received referenced to WGS 84 geographic, NAD 83 geographic, NAD 83 Louisiana State Plane (feet) and NAD 83 UTM Zone 16 or 15 N horizontal datums. The relationships and transformational equations between these horizontal datums are well established. Data were converted to a horizontal datum of NAD 83 geographic using Proj4 and VDatum.[6]

3.2.3 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the ascii *xyz* files were reviewed for consitency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps.

[5] See "Digital Elevation Models of New Orleans, Lousiana" for more information regarding the transformation of the Louisiana lidar dataset.

[6] Proj4 (a free standard Unix filter function which converts geographic longitude and latitude coordinates into cartesian coordinates, $(\lambda, \phi) \rightarrow$ (x, y), by means of a wide variety of cartographic projection functions) was used to horizontally transform datasets that originated in a State Plane datum before vertical transformations were performed using VDatum, which did not support state plane transformations at the time of development.

4 STRUCTURED DEM DEVELOPMENT

4.1 Smoothing of bathymetric data

The NOS hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Southern Louisiana DEMs. This is especially true deep forwater surveys in the Gulf of Mexico and shallow water surveys in lakes and bayous where data have point spacing up to 350 meters apart. In order to reduce the effect of artifacts created in the DEM by the low-resolution NOS datasets, and to provide effective interpolation in the deep water and into the coastal zone, a 1/3 arc-second-pre-surface bathymetric grid was generated using Generic Mapping Tools (GMT)[7]. The coastline elevation value was set at 0 meters to ensure a bathymetric surface below zero in areas where data are sparse or non-existent.

The point data were median-averaged using the GMT command 'blockmedian' to create a 1/3 arc-second grid 0.05 degrees (∼5%) larger than the Southern Louisiana DEM gridding region. The GMT command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The GMT grid created by 'surface' was converted to an ESRI Arc ASCII grid file, and clipped to the final coastline (to eliminate data interpolation into land areas) using GDAL. The resulting surface was compared with original NOS soundings to ensure grid accuracy (Figure 8), and then exported as an *xyz* file for use in the final gridding process (Table 6).

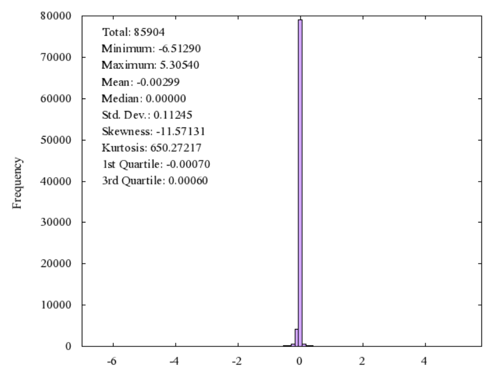


Figure 8: *Histogram of the differences between the NOS hydrographic soundings and the Southern Louisiana bathymetric surface.*

4.2 Building the NAVD 88 Structured DEM

MB-System[8] was used to create the 1/3 arc-second Southern Louisiana NAVD 88 DEM. The MB-System command 'mbgrid' was used to apply a tight spline tension to the *xyz* data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 6. The resulting binary grid was converted to an Arc ASCII grid using the MB-System tool mbm_grd2arc to create the final 1/3 arc-second Southern Louisiana NAVD 88 DEM. Figure 9 illustrates cells in the DEM that have interpolated values (shown as white) versus data contributing to the cell value (shown as black).

[7]GMT is an open source collection of ∼60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ∼30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from GMT web site.]

[8]MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (point and access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994–1997), NOAA (2002–2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from MB-System web site.]

Table 6: Data hierarchy used to assign gridding weight in MB-System

Dataset	*Relative Gridding Weight*
CSC levees lidar	25
CSC fall gulf coast lidar	25
CSC bathymetric-topographic lidar	25
Louisiana lidar	20
CSC USGS ATM lidar	20
NOS hydrographic surveys	10
NOS high-resolution BAG surveys	10
Pre-surfaced bathymetric grid	5
USACE hydrographic surveys	1
Bathymetric and Topographic Digitized features	1

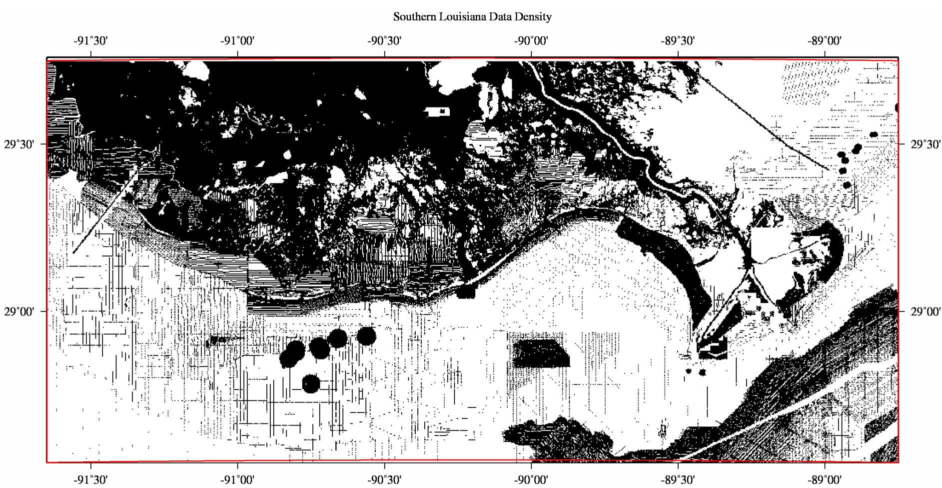


Figure 9: *Data density of Southern Louisiana; Areas where source data were available are depicted in black; areas where grid interpolation was necessary are depicted in white. Areas of sparse data density are difficult to see at the current scale.*

4.3 Building the MHW Structured DEM

The MHW DEM was created by adding the 'NAVD 88 to MHW' conversion grid to the NAVD 88 DEM.

4.3.1 Developing the conversion grid

Using extents slightly larger (∼5%) than the Southern Louisiana project area, an initial *xyz* file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The GMT command 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-grid was then converted to an intermediate *xyz* file using the GMT command 'grd2xyz'. Conversion values from NAVD 88 to MHW at each *xyz* point were generated using VDatum and the null values were removed.

The median-averaged *xyz* file was then interpolated with the GMT command 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents of the Southern Louisiana project area. NGDC then used the GMT command 'surface' to interpolate values that represented the differences between the two datums onshore to the DEM extents (Figure 10).

4.3.2 Assessing accuracy of conversion grid

The 'NAVD 88 to MHW' conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLW and MLLW to NAVD 88 using VDatum. The

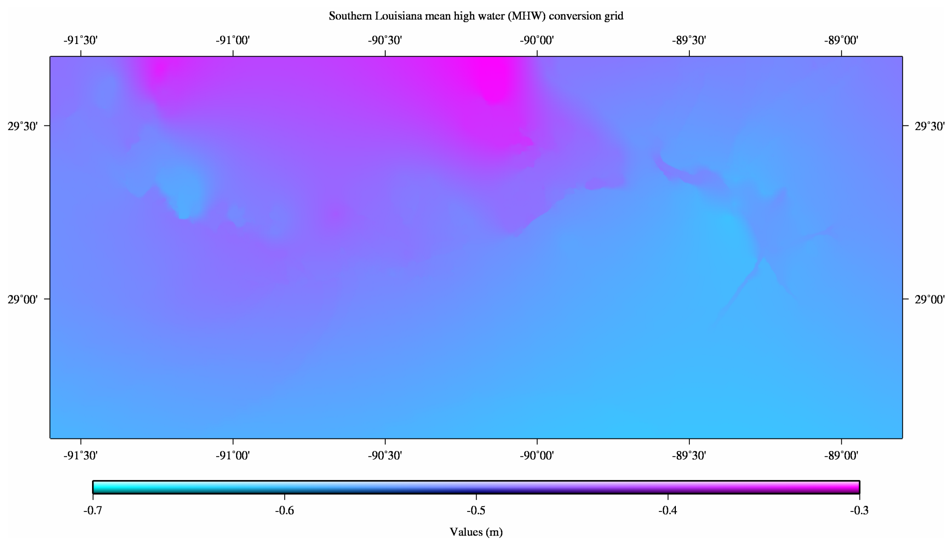


Figure 10: *Elevation conversion values of 'NAVD 88 to MHW' conversion grid derived from VDatum. Values equal the difference between NAVD 88 and MHW.*

resultant *xyz* files were filtered to remove any null values and then were merged together to form a single *xyz* file of the NOS hydrographic survey data with a vertical datum of NAVD 88. A second *xyz* file of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 *xyz* files were computed.

To verify the conversion grid methodology, the difference *xyz* file was used to generate a histogram using Gnuplot[9] to evaluate the performance of the 1/3 arc-second conversion grid by comparing 'NAVD 88 to MHW' grid to the combined difference *xyz* files from the VDatum project area (Fig. 11). Errors in the vertical datum conversion method will reside for the most part in the 'NAVD 88 to MHW' conversion grid, as the topographic data are already referenced to NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

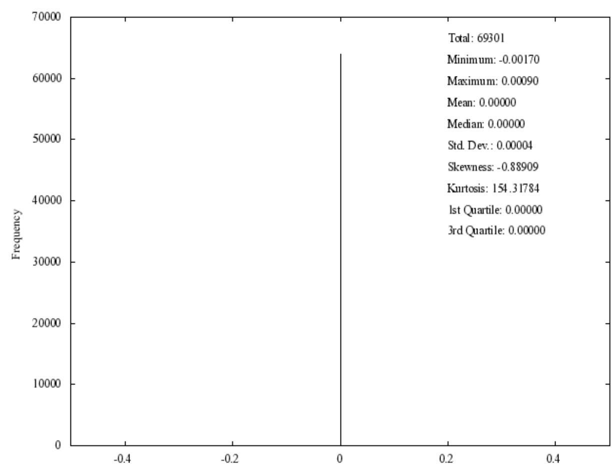


Figure 11: *Histogram of the differences between the conversion grid and xyz difference files using NOS hydrographic survey data.*

[9]Gnuplot is an open-source command-driven interactive function plotting program. It can be used to plot functions and data points in both two- and three-dimensional plots in many different formats. It is designed primarily for the visual display of scientific data.

4.3.3 Creating the MHW structured DEM

Once the NAVD 88 structured DEM was completed and assessed for errors, the conversion grid was added to it using the GMT command 'grdmath'. The resulting MHW structured DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI World 2D imagery.

4.4 Quality Assessment of the structured DEMs

4.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Southern Louisiana DEMs are dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM. The horizontal accuracy is 10 meters where topographic lidar datasets contribute to the DEM cell value. The horizontal accuracy is 0.75 meters at 1 sigma where bathymetric onlytopographic lidar-derived data contributes to the DEM cell value. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub aerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys; and by the morphologic change that occurs in this dynamic region.

4.4.2 Vertical accuracy

Vertical accuracy of the Southern Louisiana DEMs are also highly dependent upon the source datasets contributing to DEM cell values. Topographic lidar has an estimated RMSE of 13.9 to 20 cm. Bathymetrictopographic lidar-derived data have a vertical accuracy of 0.20 meters at 1 sigma. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations.

4.4.3 Slope maps and 3D perspectives

GMT was used to generate a slope grid from the Southern Louisiana NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Figure 12). The DEM was transformed to UTM Zone 15 North coordinates (horizontal units in meters) in GDAL for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using QTModeler. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 13 shows a perspective view image of the 1/3 arc-second Southern Louisiana NAVD 88 DEM in its final version.

4.4.4 Comparison with National Geodetic Survey geodetic monuments

The elevations of 80 NOAA NGS geodetic monuments (Figure 14a) were extracted from online shapefiles of NGS Geodetic monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monument elevations were compared with elevations of the Southern Louisiana NAVD 88 DEM. Differences between the DEM elevations and the NGS geodetic monument elevations range from -1.4 to 1.5 meters, with the majority of them being within +/-1 meter (Figure 14b). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of an observation tower, light house or at the apex of other structures.

4.4.5 Comparison with source data files

To ensure grid accuracy, the Southern Louisiana NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the DEM using Python, GDAL and Gnuplot. Histograms of the differences between individual datasets and the DEM are shown in Figure 4.4.5. Largest differences between source datasets and the DEM resulted from the averaging of multiple topographic source datasets where data coverage overlapped, particularly in regions of steep slopes.

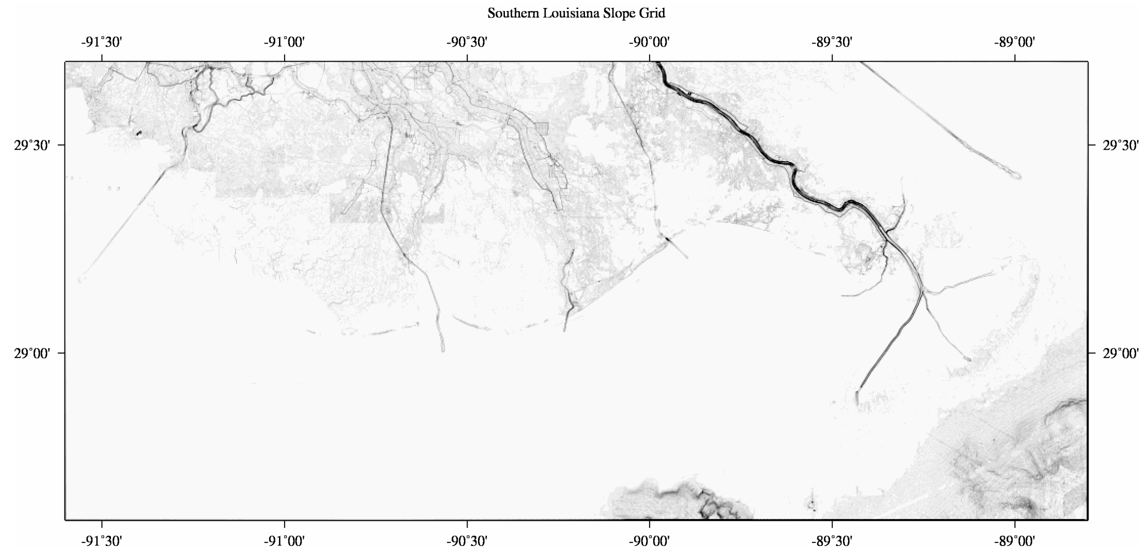


Figure 12: *Slope map of the Southern Louisiana NAVD 88 DEM. Flat-lying slopes are white; dark shading denotes steep slopes.*

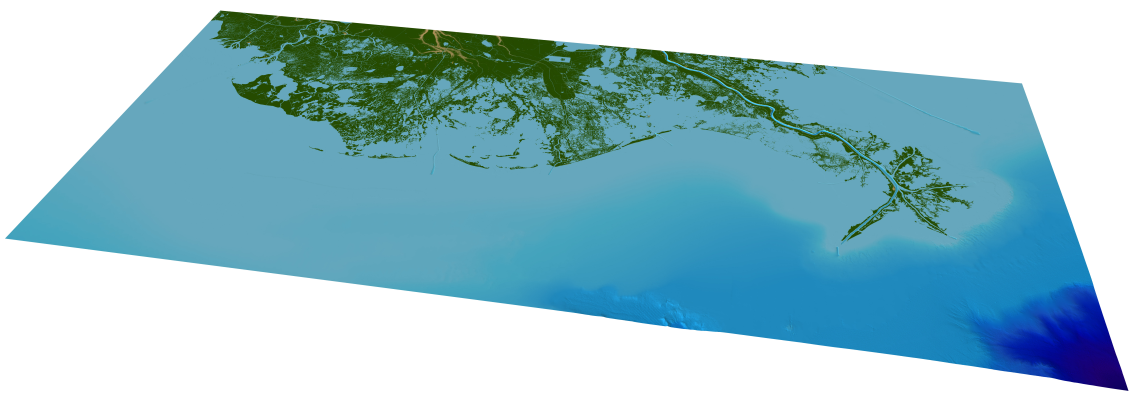
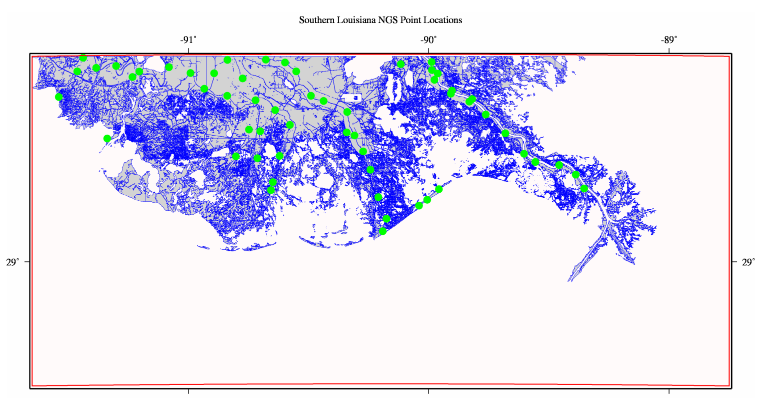
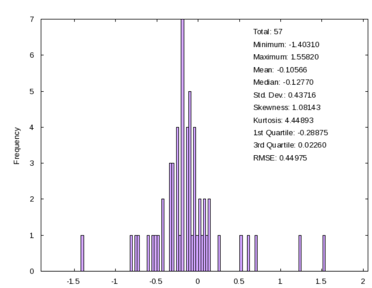


Figure 13: *Perspective view from the southwest of the Southern Louisiana NAVD 88 DEM. Fifteen times vertical exaggeration.*

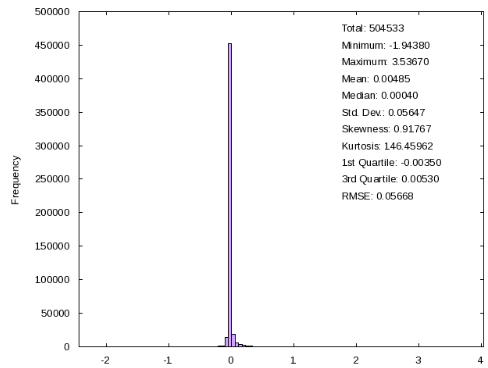


(a) *Locations of NGS monuments used in the evaluation of the Southern Louisiana DEMs.*

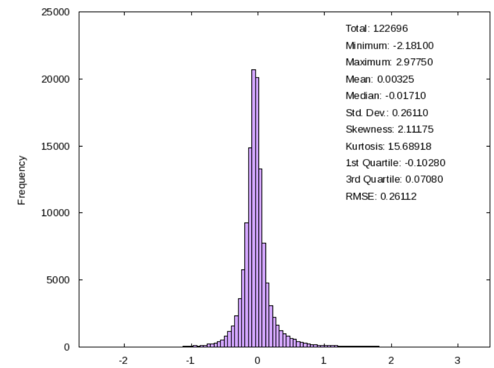


(b) *Histogram of the differences between the NGS monument elevation values and the Southern Louisiana DEM*

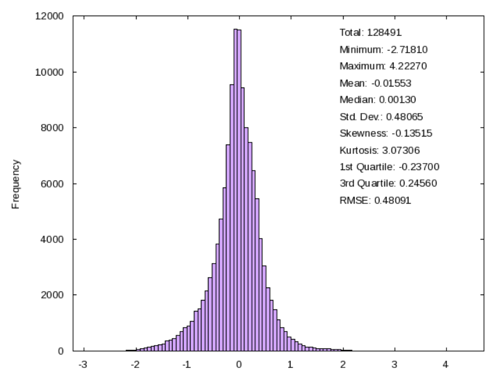
Figure 14: *Comparison with National Geodetic Survey geodetic monuments, locations and histogram.*



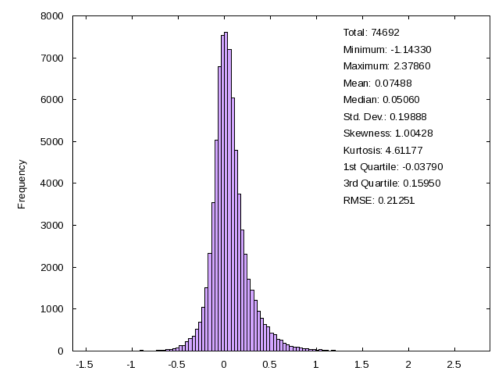
(a) *Histogram of the differences between a subset of the Louisiana lidar dataset and the Southern Louisiana NAVD 88 DEM*



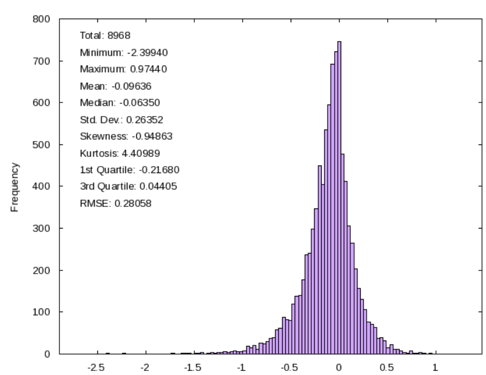
(b) *Histogram of the differences between the CSC Topo/Bathy lidar dataset and the Southern Louisiana NAVD 88 DEM*



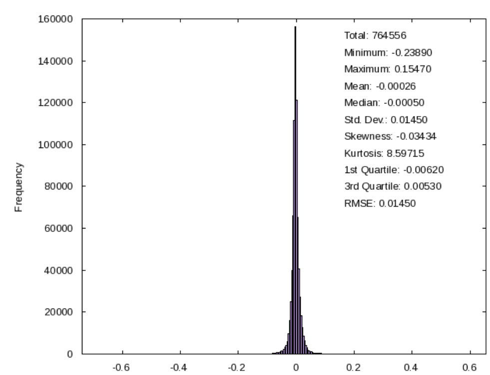
(c) *Histogram of the differences between the CSC Post-Katrina levee lidar dataset and the Southern Louisiana NAVD 88 DEM*



(d) *Histogram of the differences between the CSC USGS ATM lidar dataset and the Southern Louisiana NAVD 88 DEM*



(e) *Histogram of the differences between the ENC hydrographic dataset and the Southern Louisiana NAVD 88 DEM*



(f) *Histogram of the differences between the High Resolution NOS BAG hydrographic dataset and the Southern Louisiana NAVD 88 DEM*

Figure 15: *Hisograms of the differences between individual datasets and the Southern Louisiana NAVD 88 DEM.*

5 UNSTRUCTURED DEM DEVELOPMENT

5.1 Building the NAVD 88 Unstructured DEM

The cleaned and transformed *xyz* source data (Section 3) as well as the final NAVD 88 structured DEM (Section 4) were used in the development of the unstructured DEM. The NAVD 88 structured DEM was used to generate density and curvature grids, using Python and the GMT command 'grdgradient', respectively, which were then used to generate standardized normal[10] grids (Figures 16 through 19) for use in defining regional domains (Figure 20) throughout the studay area.

The regional domains were developed into raster format using Python and GDAL for the extraction and down-sampling of the original source *xyz* data. The sampled *xyz* dataset was used to build a preliminary unstructured grid using Shewchuk's Triangle[11] program, constraining the triangles to a minimum angle of 20 degrees. To meet the 20 degree requirement Triangle adds steiner points to the source *xyz* dataset. The steiner points were were sampled against the structured NAVD 88 DEM to extract the elevation value for each additional point. The steiner points were then added to the source *xyz* dataset for further processing. The GMT command 'triangulate' was used to triangulate the source *xyz* dataset (21, using the sampled steiner points, and create the final NAVD 88 unstructured DEM. The GDAL command 'ogr2ogr' was used to convert the GMT generated triangles to ESRI Shapefiles. See Appendix A for additional details regarding the methodology of building the unstructured DEM.

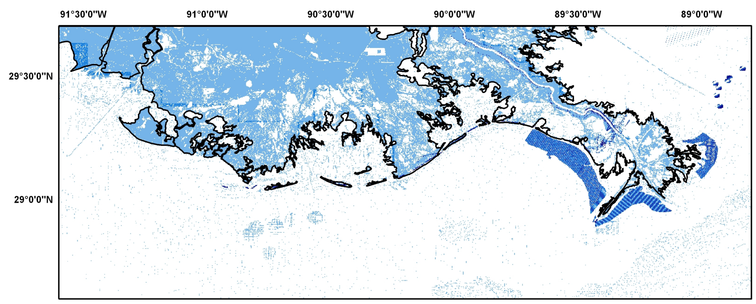


Figure 16: *Data Density Plot. Dark blue indicates highest density; light blue indicates lowest density. White ares indicate regions of no data. Due to the scale of the image, regions of sparse data may not be visible in the graphic. Coastline from the National Operational Hydrologic Remote Sensing Center (NOHRSC; http://www.nohrsc.noaa.gov/gisdatasets/) shown in black.*

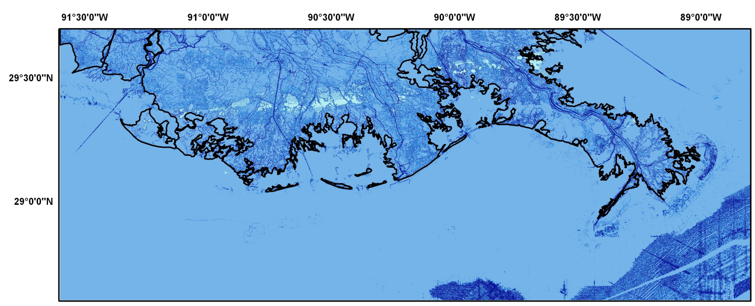


Figure 17: *Curvature plot. Dark blue indicates largest curvature; light blue indicates lowest curvature. Coastline from the National Operational Hydrologic Remote Sensing Center (NOHRSC) shown in black.*

[10]Standard Normal refers to a distribution where μ (Mean) = 0 and σ^2 (Variance)= 1

[11]Triangle generates exact Delaunay triangulations, constrained Delaunay triangulations, conforming Delaunay triangulations, Voronoi diagrams, and high-quality triangular meshes. The latter can be generated with no small or large angles, and are thus suitable for finite element analysis.

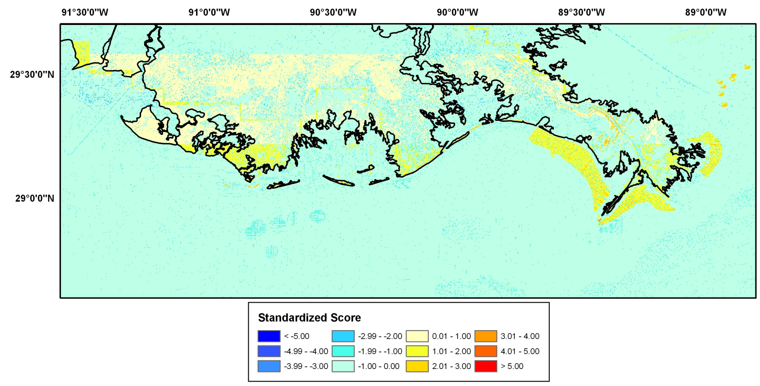


Figure 18: *Standard normal scores of data density. Cool colors indicate regions with density less than the mean. Warm colors indicate regions with greater density than the mean. Due to the scale of the image, regions of sparse data may not be visible in the graphic. Coastline from the National Operational Hydrologic Remote Sensing Center (NOHRSC) shown in black.*

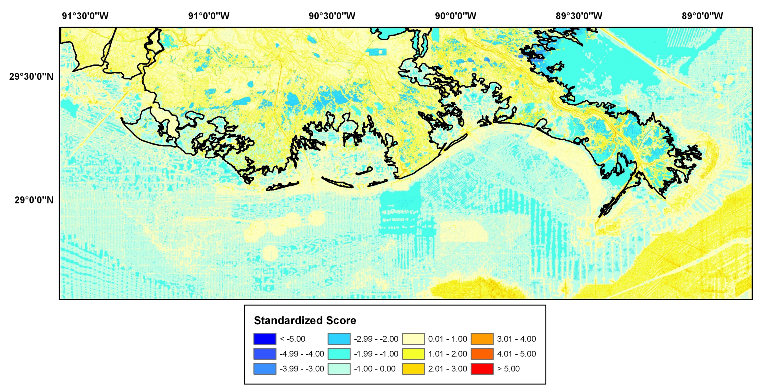


Figure 19: *Standard normal scores of curvature. Cool colors indicate regions less than the mean curvature. Warm colors indicate regions with greater curvature than the mean. Coastline from the National Operational Hydrologic Remote Sensing Center (NOHRSC) shown in black.*

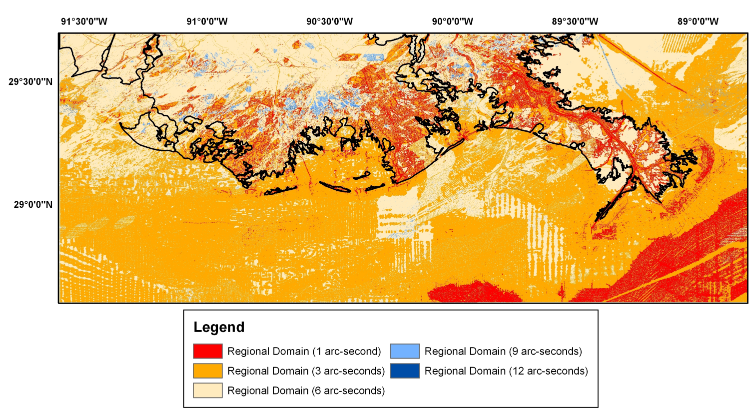


Figure 20: *Regional Domains. Highest resolution shown in warm colors, lowest resolution in cool colors, default resolution of 6 arc-seconds shown in beige. Coastline from the National Operational Hydrologic Remote Sensing Center (NOHRSC) shown in black.*

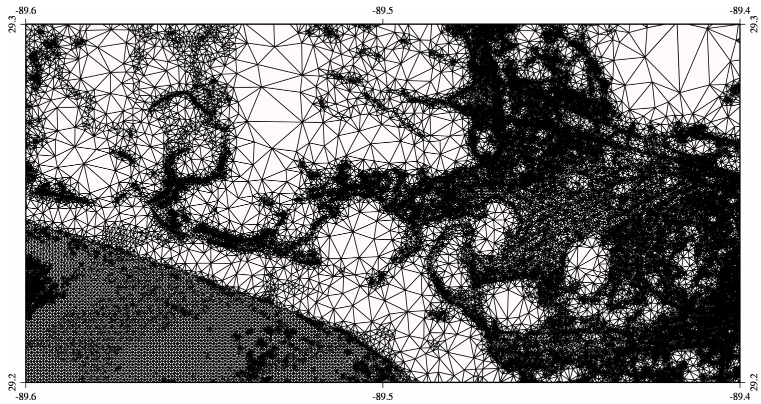


Figure 21: *Portion of the final DEM triangle vectors.*

5.2 Building the MHW Unstructured DEM

The MHW unstructured DEM was created by adding a 'NAVD 88 to MHW' conversion grid of the project area to the NAVD 88 vector nodes, using Python and GDAL. See Section 4.3 regarding the methodology used in creating the 'NAVD 88 to MHW' conversion grid.

5.3 Quality Assessment of the Unstructured DEMs

The final *xyz* nodes produced for the NAVD 88 unstructured DEM were compared to the NAVD 88 structured DEM to determine the relative accuracy of the unstructured gridding method using Python and GDAL. A histogram of the differences between the input dataset and the Southern Louisiana NAVD 88 structured DEM is shown in Figure 22. The largest differences between the source dataset and the structured DEM are the result of the averaging of multiple source datasets where data coverage overlapped, particularly in regions of steep slopes.

The final triangle GMT vectors produced for the DEM were converted to ESRI shapefiles to allow for graphical viewing in ESRI ArcMap. The vector nodes were viewed along with the triangles to make sure the nodes had not been shifted and that they were correctly placed along the intersections of the triangles. The triangles were also checked for dangles, overshot lines, and other anomolies that can occur during triangulation.

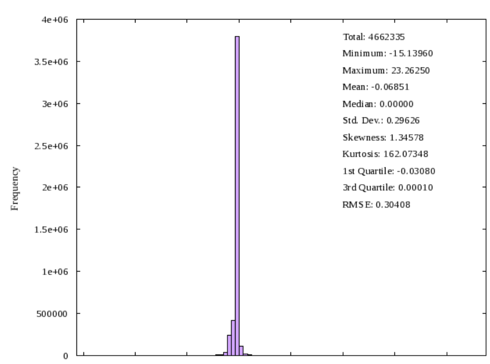


Figure 22: *Histogram of the differences between the source xyz dataset used in the construction of the NAVD 88 unstructured DEM and the final NAVD 88 structured DEM.*

6 SUMMARY AND CONCLUSIONS

Two bathymetric-topographic structured digital elevation models of the Southern Louisiana region, with cell spacing of 1/3 arc-second, and vertical datums of NAVD 88 and MHW and two bathymetric-topographic unstructured digital elevation models were developed for HFIP. The DEMs were developed for the purpose of building companion structured and unstructured DEMs, and were developed to be used for storm surge inundation and sea level rise modeling. The best available digital data from U.S. federal, state and local agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, GMT, MB-System, Quick Terrain Modeler, GDAL, Proj4, VDatum, and Gnuplot software. NGDC developed a conversion grid derived from the VDatum project area that transformed the Southern Louisiana NAVD 88 DEMs to MHW.

The utility of the standardized curvature and density grids, in the building of the unstructured DEMs, is restricted by the assumption that the values within each grid have a normal distribution. While this may be the case in most locations, in southern Louisiana where the topography is flat and recent lidar provides dense data coverage, the distributions are more likely highly skewed (e.g., gamma, exponential). As a result, the normality assumption is possibly not valid. Standard deviations could instead be computed relative to an appropriate distribution, improving the definition of regional domains to mitigate over-sampling in regions of moderate curvature and data density.

Due to the nature of the raster development, in order to establish regional domains it is imperative that the final unstructured grid be developed using an *xyz* dataset that does not include the bathymetric pre-surface grid (section 4.1) used in the structured DEM development process. The bathymetric grid provides *xyz* data at 1/3 arc-second resolution and generates unrealistically high resolution in regions where no actual data exist. Also, the use of the GMT 'blockmedian' command on spatially dense *xyz* data (e.g., lidar) creates distinguishable, approximately square-cell patterns in the unstructured grid.

Recommendations to improve the Southern Louisiana DEMs, based on NGDCs research and analysis, are listed below:

- Process USACE 2005 Post-Hurricane Katrina Topographic Mapping lidar to bare-earth.
- Conduct topographic lidar surveys for all near-shore regions.
- Conduct NOS hydrographic surveys in hydrographic data gaps and in estuary bays and rivers.
- Conduct topographic surveys of coastal marsh-lands.

7 ACKNOWLEDGEMENTS

The development of the Southern Louisiana DEMs was funded by the Hurricane Forecast Improvement Project (HFIP). The authors thank Jay Ratcliff of the United States Army Corps of Engineers for supplying otherwise unavailable bathymetric surveys as well as Jesse Feyen, Maureen Kenny (NOAA CSDL), Yinglong "Joseph" Zhang (CMPO) and Rob Witter (DOGAMI).

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Shewchuk, J.R., 2002: Delaunay Refinement Algorithms for Triangu.ar Mesh Generation, Computational Geometry: Theory and Applications, 22, 21–74.

Love, M.R., et. al, 2009: Digital Elevation Models of New Orleans, Louisiana: Procedures, Data Sources and Analysis.

9 DATA PROCESSING SOFTWARE

ArcGIS 9.3, developed and liscensed by ESRI, Redlands, California, http://www.esri.com

ESRI World Imagery - ESRI ArcGIS Resource Centers, http://www.esri.com

GEODAS v. 5 - Geophysical Data System, free software developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas

GMT v. 4.1.4 - Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com

GDAL v. 1.7.1 Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org

Proj4 v. 4.7.0 free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/

Triangle v. 1.6 Triangle generates exact Delaunay triangulations, constrained Delaunay triangulations, conforming Delaunay triangulations, Voronoi diagrams, and high-quality triangular meshes. The latter can be generated with no small or large angles, and are thus suitable for finite element analysis, http://www.cs.cmu.edu/~quake/triangle.html

VDatum v. 2.3 developed and maintained by NOAAs National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/

A APPENDIX A

A.1 Introduction

Modeling and mapping of coastal processes (e.g., tsunamis, hurricane storm-surge, and sea-level rise) requires digital representations of Earth's solid surface, referred to as digital elevation models (DEMs). Some modeling utilizes structured, square-cell DEMs, while others would benefit from unstructured DEMs that have no regular cell size or pattern. Usually, these different DEM types are developed independently, even though they are built from the same source bathymetric and topographic datasets. NOAA's National Geophysical Data Center (NGDC) created, tested and reviewed a new DEM development methodology to build companion structured and unstructured DEMs of southern Louisiana that will benefit diverse coastal inundation modeling and mapping efforts. The intent of the project was to develop a methodology to build both DEM types from the same source elevation datasets, which could be used as a model for future DEM development projects.

As shown in Figure A-1, the structured DEM is used to generate density and gradient grids for defining regional domains. These regional domains are then converted to rasters for extracting and down-sampling the source data to an appropriate resolution.[12] The purpose of this appendix is to describe the methodology used to generate an unstructured grid from the source datasets used in building the structured DEM of southern Louisiana (Figure A-1).

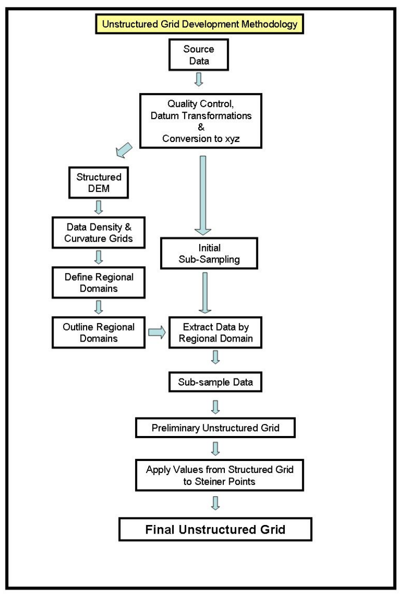


Figure A-1: *Flow chart of the unstructured grid development methodology.*

A.2 Unstructured DEM Development and Methodology

Southern Louisiana has extraordinary data coverage, particularly over land areas, where post-Katrina lidar surveys have been conducted since 2005. The abundance of data for the region provides a computational challenge in the generation of structured, and particularly, unstructured grids. For the entire study area, the total estimated file size of the source datasets exceeds 5 GB - much larger than most commercial software packages can ingest due to limitations of available RAM. Given this limitation, NGDC selected open source, GNU/Linux-based applications to improve time efficiency and enhance the portability of the software. NGDC also used the GMT tool 'blockmedian' to reduce the initial file size to fewer than 2.5 GB by sub-sampling the lidar data to 1 arc-second prior to developing the unstructured DEM.

[12] 'Appropriate resolution' depends on user needs as well as source data size and locational geo-morphology.

A.2.1 Build Structured DEM

The southern Louisiana, structured DEM was constructed to meet the NOAA Coast Survey Development Laboratory specifications, based on storm surge and sea-level-rise modeling requirements. The structured DEM was developed at 1/3 arc-second (∼10m cell size) with extents of 28.6 to 29.76 N and 91.6 to 88.8 W. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum 1983 (NAD 83) and North American Vertical Datum (NAVD 88). NGDC used NOAA's vertical datum transformation tool (VDatum; http://vdatum.noaa.gov/) for all vertical datum transformations of source datasets. Data were gathered in an area slightly larger (∼5%) than the DEM extents. This data "buffer" ensures that gridding occurs across, rather than along, the DEM boundaries to prevent edge effects. Additional information on the development methodology for the southern Louisiana structured grid can be found in the main portion of this report.

A.2.2 Determine Curvature and Data Density

During the generation of the structured DEM, NGDC used the command 'mbgrid' in MB-System with the flag '-M' invoked to make two additional grids. One grid contains the standard deviation of the data within each grid cell relative to the grid value. The second, a density grid, contains the number of data points in each grid cell (Figure A-3). The structured DEM is also used to compute a slope magnitude and an azimuth grid using the GMT command 'grdgradient'. The gradient, or derivative of the slope, grid is then generated in a similar manner using 'grdgradient' on the slope magnitude grid (Figure A-4). The 'grdhistreq' command in GMT is subsequently used to produce grids of standardized normal values from both the density grid from MB-System and the gradient grid from GMT (Figures A-5 and A-6).

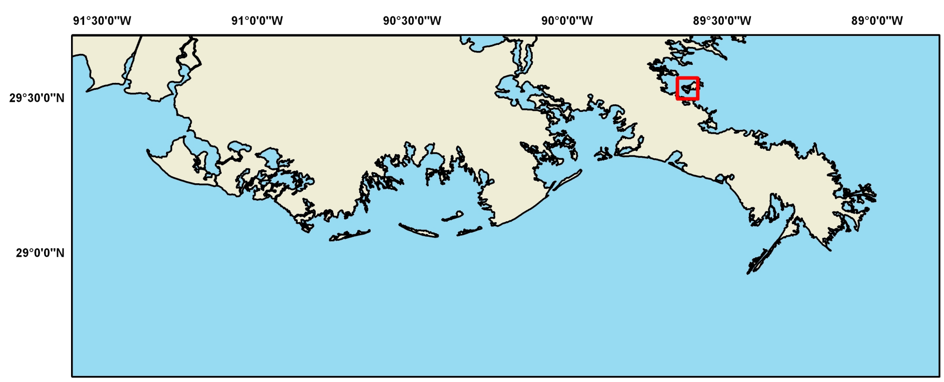


Figure A-2: *Location of the example for increased resolution (IR) to meet minimum angle triangulation constraints. Land areas in beige; water areas shown in blue. Coastline from the NOHRSC is in black.*

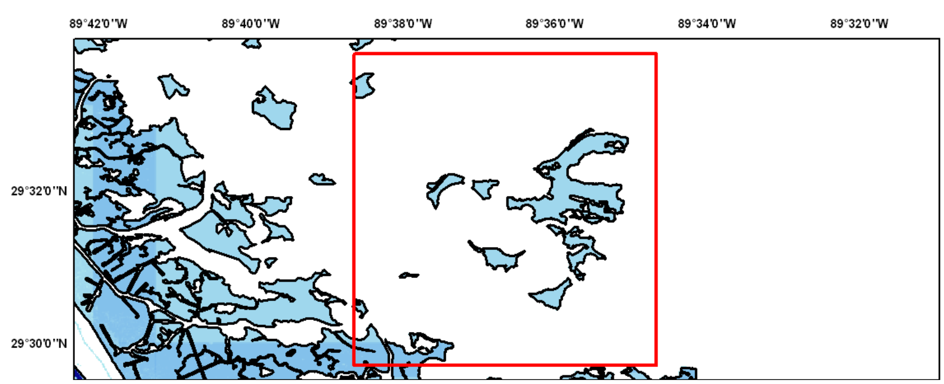


Figure A-3: *Data density plot. Dark blue indicates highest density; light blue indicates lowest density. Grey areas indicate regions of no data. Due to the scale of the image, regions of sparse data may not be visible in the graphic. Coastline from the NOHRSC shown in black.*

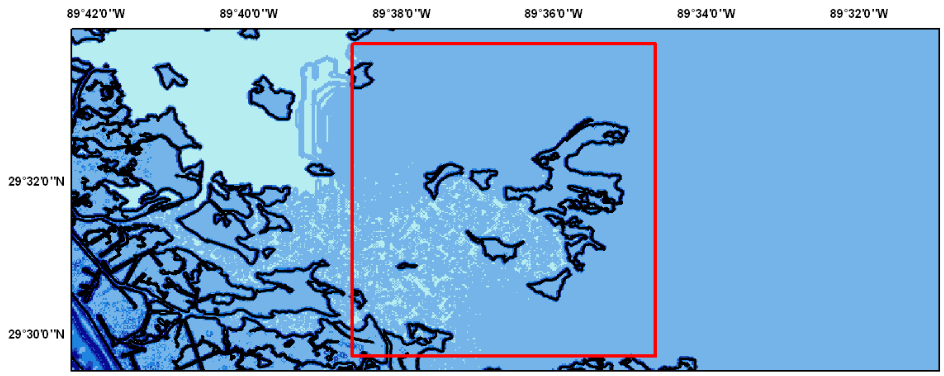


Figure A-4: *Curvature magnitude plot. Dark blue indicates largest gradients; light blue indicates lowest gradients. Coastline from the NOHRSC shown in black.*

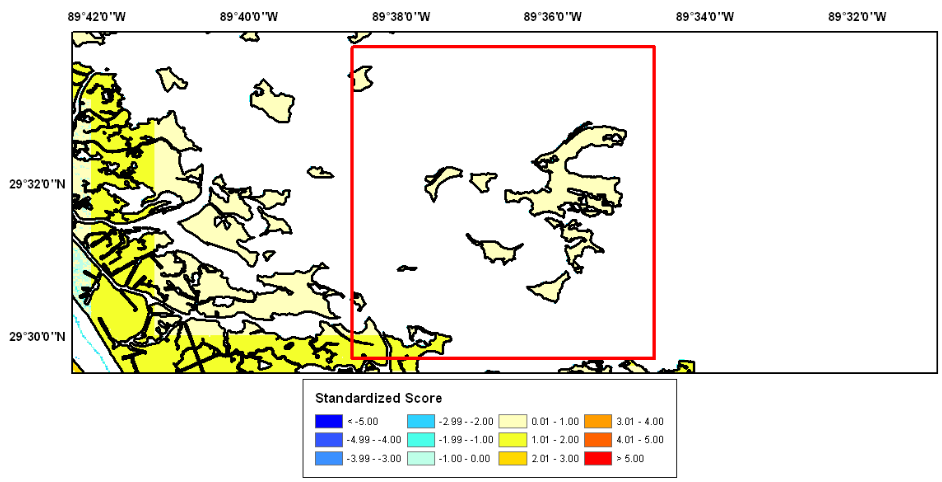


Figure A-5: *Standard normal scores of data density. Cool colors indicate regions with density less than the mean. Warm colors indicate regions with greater density than the mean. Grey areas indicate regions of no data. Due to the scale of the image, regions of sparse data may not be visible in the graphic. Coastline from the NOHRSC shown in black.*

A.2.3 Define Regional Domains

Using the standard normal value (s) allows for the identification of regions of similar gradient and density. From the standard normal distribution, approximately 68 percent of the values will fall within +/- 1 standard deviation with approximately 95 percent of values between +/- 2 standard deviations (Figure A-7). Using this relationship, a decision matrix (Table A-1) was developed to automatically identify regions based on data density (d) and gradient magnitude (m). After converting the gradient and density grids (see Figure A-5) to xym and xyd files, respectively, an assigned value was given based on the standardized score from each grid.

The assigned values from the xym and xyd files were then combined to provide a discrete, cumulative score (C) between -4 and +4 as an indicator for increasing the resolution (positive values) or decreasing the resolution (negative values) relative to a user-defined, default resolution for the unstructured grid (Table A-2). For the study area, the default value was prescribed as 6 arc-seconds, representing areas with average gradient and data density.

A.2.4 Outline Regional Domains

Using the cumulative scores derived in Section A2.3, the cumulative score xyC data were then parsed into individual files based on the proposed resolution (e.g., 1 arc-second, 3 arc-seconds, etc.). Using Python and GDAL,

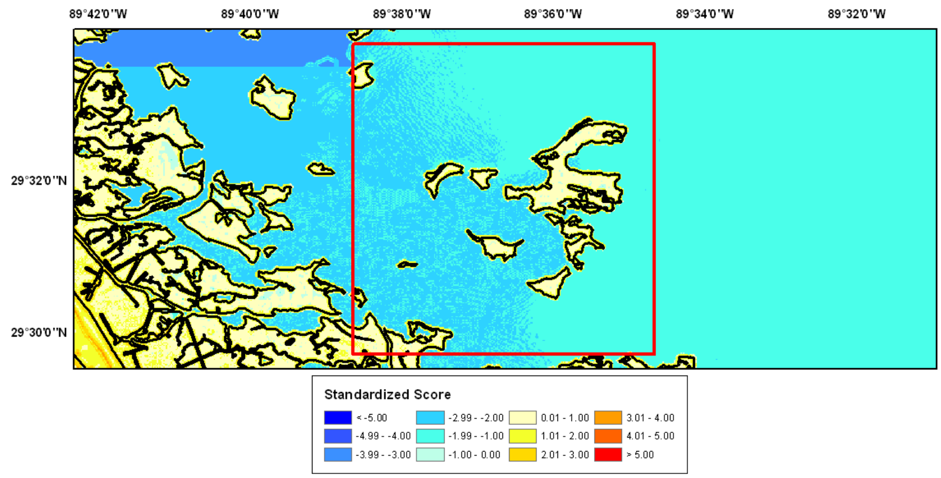


Figure A-6: *Standard normal scores of curvature. Cool colors indicate regions less than the mean curvature. Warm colors indicate regions with greater curvature than the mean. Coastline from the NOHRSC shown in black.*

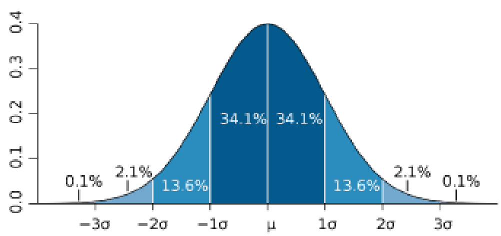


Figure A-7: *Standard normal distribution. Fractional area under the curve at each standard deviation (g) noted by blue shading and percentages. Source: http://en.wikipedia.org/wiki/File:Standard_deviation_diagram.svg*

Table A-1: Interpretation of standardized scores used to develop regional domains.

Standardized Value	*Assigned Value*	*Density-Gradient Interpretation*
$s \geq 2$	2	Much above average
$1<s>2$	1	Above average
$-1 \leq s \leq 1$	0	Average
$-2<s<-1$	-1	Below average
$s \leq -12$	-22	Much below average

Table A-2: Relationship between cumulative score and resolution.

Cumulative Score	*Resolution (Arc-Seconds)*
3 or 4	1
2	3
-1, 0, or 1	6 (default)
-2	9
-3 or -4	12

individual rasters were created for each resolution at the highest proposed resolution of 1 arc-second (Figure A-8). The 1 arc-second resolution rasters provide minimal overlap of different resolution rasters and reduce the potential for sampling individual points at more than one resolution.

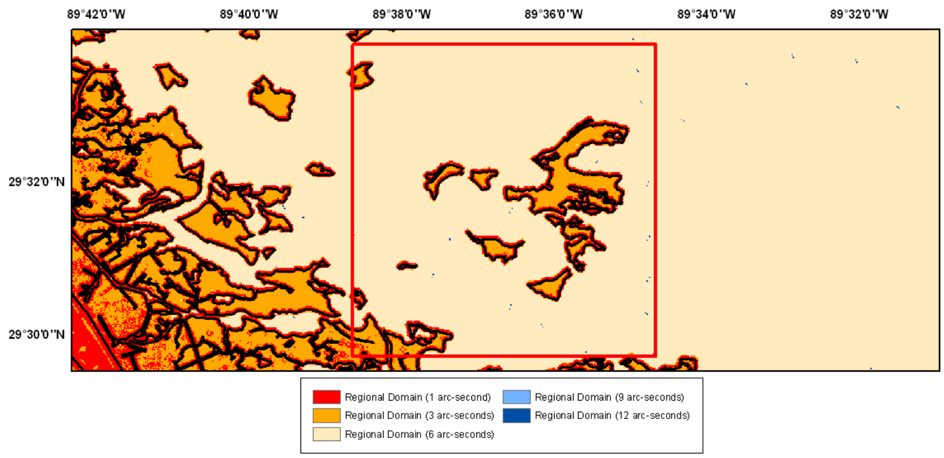


Figure A-8: *Regional domains. Highest resolution shown in warm colors, lowest resolution in cool colors, default resolution of 6 arc-seconds shown in beige. Coastline from the NOHRSC is in black.*

A.2.5 Down-sample the Source Elevation Data

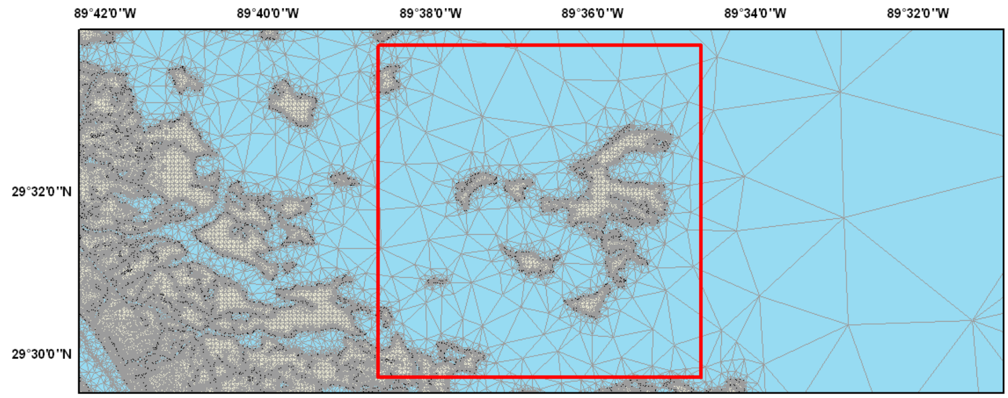
The lidar data used in the structured DEM were first sub-sampled to 1 arc-second using the GMT tool 'blockmedian'. The remaining input source data remained in their native resolution. By default, the 'blockmedian' command outputs a median position and elevation value at a minimum of the selected resolution. The regional domain rasters were then used to extract data from the sub-sampled source data files. The process was iterative with selected data points removed from the potential source data for each subsequent (i.e., lower) resolution. The intent was to eliminate any potential overlapping of data from differing domain resolutions, which may artificially increase the resolution in the final unstructured grid.

Once the individual resolution *xyz* files were created, the data were sub-sampled again, where necessary, to the appropriate resolution using the GMT 'blockmedian'. The resulting size of the final dataset for the test area was approximately 20 percent of the original input.

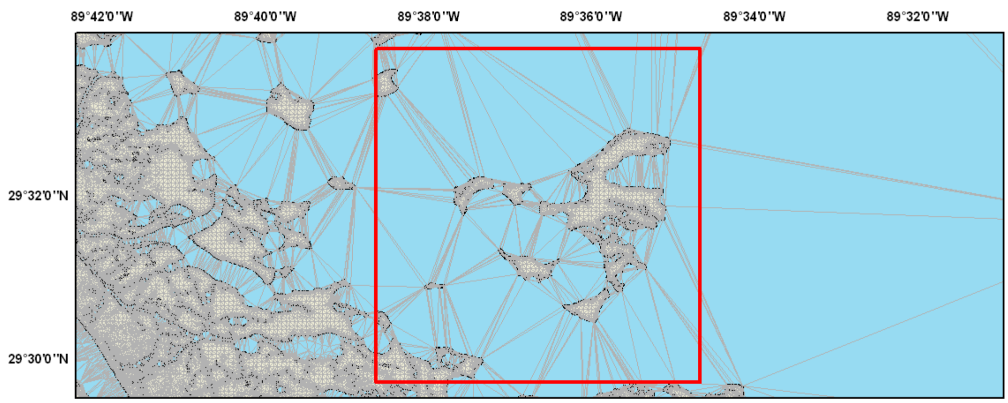
A.2.6 Build Preliminary Unstructured Grid

The domain-specific *xyz* files resulting from 'blockmedian' are concatenated with points extracted at 2 arc-seconds along the structured grid boundary. These points serve as input in the Triangle software, developed and available online from Shewchuk (1996 and 2002; http://www.cs.cmu.edu/ quake/triangle.html). Each row of the concatenated input data file generated must be appended with row number and a header containing the number of rows, dimensions, number of attributes (e.g., 1 for elevation), and number of boundary markers (in this case zero). This code generates a conforming, constrained Delaunay triangulation when given the minimum angle constraint of 20 degrees. The result is an unstructured grid that provides increased resolution in regions of increased gradient and data density, but also in regions where required to meet triangulation constraints based on the spatial distribution of the input dataset (e.g., see Figures A-9b through A-9a). Steiner points are inserted to meet the minimum angle constraints and define the edges of supplementary triangles required to maintain the Delaunay property. The Steiner points are assigned values initially through linear interpolation (see Section A2.7). The final output from Triangle is two ASCII format files. One file contains the nodes with elevations. The other file contains the elements with respective node numbers. Only the file with the nodes is used in subsequent processing steps to develop the final unstructured grid.

To control the angles, shape and anomalies along the project boundary additional nodes were added into the node file before performing the Triangle command. The nodes were distributed around the edge of the project boundary and were spaced at the default resolution of the grid, about 60 arc-seconds. These points greatly increase the quality of the output mesh around the edges of the project area (e.g. Figures A-10a and A-10b).

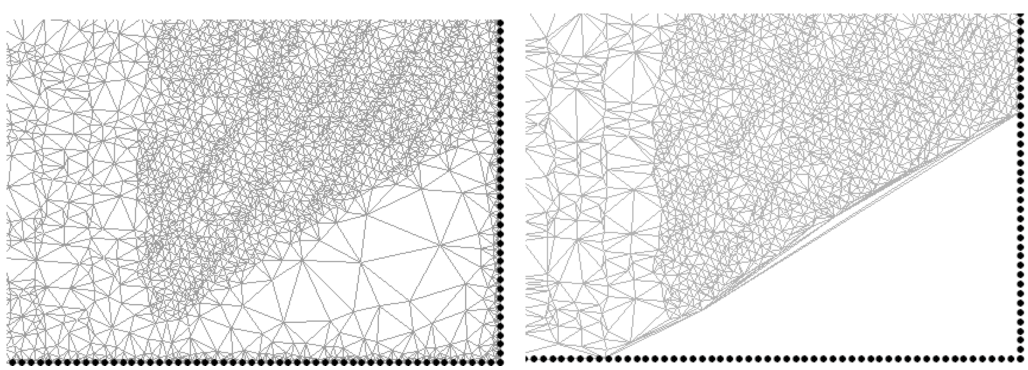


(a) *Triangulation with the insertion of Steiner points. Note the correction of the highly-skewed, skinny triangles through increased resolution in the region. Land areas shown in beige; water shown in blue. Coastline from the NOHRSC is in black. Region of interest outlined in red.*



(b) *Triangulation without the insertion of Steiner points. Note the highly-skewed, skinny triangles that result from the spatial distribution of the input data points. Land areas shown in beige; water shown in blue. Coastline from the NOHRSC is in black. Region of interest outlined in red.*

Figure A-9: *Triangulation with (a) and without (b) the insertion of Steiner points.*



(a) *Triangle output when using project area bounding points. Bounding points at 6 arc-seconds as black dots. Map shows lower right corner of project area.*

(b) *Triangle output when not using project area bounding points. Bounding points at 6 arc-seconds as black dots. Map shows lower right corner of project area.*

Figure A-10: *Triangle output with (a) and without (b) the used of added project area bounding points.*

A.2.7 Apply Values from Structured Grid to Steiner Points

The proposed method is restricted somewhat by the original spatial distribution of the input source datasets. For example, regions with no observational data in the structured grid were filled through interpolation; therefore, those regions still contain no observations for application in the unstructured grid development (see Fig. A5). The insertion of Steiner points through the Triangle software package provides increased resolution in these regions to meet minimum angle triangulation constraints. The Steiner points are initially assigned elevations through linear interpolation; however, this can result in an incorrect representation of the actual morphology. Instead, NGDC isolated the added Steiner points and extracted values for these locations from the structured DEM. The elevation values for these points are updated in the node file from the Triangle output in Section A2.6 to produce a final node file.

A.2.8 Build Final Unstructured Grid

The final node file from Triangle is then used to create a final *xyz* file that meets the minimum angle triangulation criteria and eliminates issues from the linear interpolation of Steiner point elevations. This file is used in the GMT command 'triangulate'. The 'triangulate' command performs optimal Delauney triangulation and gridding of geographic data using the methodology of Shewchuk (1996). The output from 'triangulate' includes a structured grid and the triangle edges in an ijk format. The final *xyz* file populates the elevation value for each node in the ijk file. The resultant ijk and *xyz* files can be used to generate a polygon and point shapefile representing the edges and nodes, respectively.

A.3 Summary and Conclusions

The utility of the standardized gradient and density grids is restricted by the assumption that the values within each grid have a normal distribution. While this may be the case in most locations, in southern Louisiana where the topography is flat and recent lidar provides dense data coverage, the distributions are more likely highly skewed (e.g., gamma, exponential). As a result, the normality assumption is possibly not valid. Standard deviations could instead be computed relative to an appropriate distribution, improving the definition of regional domains to mitigate over-sampling in regions of moderate gradient and data density.

Due to the nature of the raster development described in Section A2.1.2, it is imperative that the final unstructured grid be developed using an *xyz* file that does not include the bathymetric pre-surface grid (see http://www.ngdc.noaa.gov/mgg/inundation/tsunami/general.html) used in the structured DEM development process. The bathymetric grid provides *xyz* data at 1/3 arc-second resolution and generates unrealistically high resolution in regions where no actual data exist. Finally, the use of the 'blockmedian' command on spatially dense *xyz* data (e.g., lidar) creates distinguishable, approximately square-cell patterns in the unstructured grid.

A.4 Improvements to Unstructured DEM methodology

Additional improvements to the unstructured grid development methodology could include:

- Eliminate overlapping datasets prior to generating the data density grid.
- Increase grid resolution and number of regional domains to smooth transitions between different resolution triangles.
- Identify weighting functions of density and curvature grids that best capture relevant morphologic features (e.g levees, dams).

B APPENDIX B

B.1 Bathymetric data tables

Table B-1: NOS Hydrographic datasets used in building the southern Louisiana DEMs

Survey ID	Year	Original Vertical Datum	Scale/Vertical Accuracy	Provided Horizontal Datum
H01991	1876	Undetermined	1:4800	Undetermined
H01819	1888	Undetermined	1:20,000	Undetermined
H01821	1888	Undetermined	1:20,000	Undetermined
H01822	1888	Undetermined	1:20,000	Undetermined
H02072	1891	Undetermined	1:20,000	Undetermined
H02997	1909	Undetermined	1:10,000	Undetermined
H02998	1909	Undetermined	1:10,000	Undetermined
H02998	1909	Undetermined	1:10,000	Undetermined
H02996	1909	Undetermined	1:20,000	Undetermined
H04212	1921	Undetermined	1:80,000	Undetermined
H04223	1922	Undetermined	1:80,000	Undetermined
H05491	1933	Undetermined	20,000	Undetermined
H05788	1934	Undetermined	10,000	Undetermined
H05768	1934	Undetermined	120,000	Undetermined
H05478	1934	Undetermined	20,000	Undetermined
H05479	1934	Undetermined	20,000	Undetermined
H05480	1934	Undetermined	20,000	Undetermined
H05481	1934	Undetermined	20,000	Undetermined
H05482	1934	Undetermined	20,000	Undetermined
H05490	1934	Undetermined	20,000	Undetermined
H05492	1934	Undetermined	20,000	Undetermined
H05493	1934	Undetermined	20,000	Undetermined
H05494	1934	Undetermined	20,000	Undetermined
H05495	1934	Undetermined	20,000	Undetermined
H05496	1934	Undetermined	20,000	Undetermined
H05497	1934	Undetermined	20,000	Undetermined
H05537	1934	Undetermined	20,000	Undetermined
H05539	1934	Undetermined	20,000	Undetermined
H05541	1934	Undetermined	20,000	Undetermined
H05789	1934	Undetermined	20,000	Undetermined
H05790	1934	Undetermined	20,000	Undetermined
H05764	1934	Undetermined	40,000	Undetermined
H05765	1934	Undetermined	40,000	Undetermined
H05767	1934	Undetermined	80,000	Undetermined
H05828	1935	Undetermined	10,000	Undetermined
H05939	1935	Undetermined	120,000	Undetermined
H05538	1935	Undetermined	20,000	Undetermined
H05824	1935	Undetermined	20,000	Undetermined
H05826	1935	Undetermined	20,000	Undetermined
H05827	1935	Undetermined	20,000	Undetermined
H05837	1935	Undetermined	20,000	Undetermined
H05838	1935	Undetermined	20,000	Undetermined
H05852	1935	Undetermined	20,000	Undetermined

Table B-1: NOS Hydrographic datasets used in building the southern Louisiana DEMs

Survey ID	Year	Original Vertical Datum	Scale/Vertical Accuracy	Provided Horizontal Datum
H05859	1935	Undetermined	20,000	Undetermined
H05766	1935	Undetermined	40,000	Undetermined
H05953	1935	Undetermined	40,000	Undetermined
H05954	1935	Undetermined	40,000	Undetermined
H05955	1935	Undetermined	40,000	Undetermined
H05938	1935	Undetermined	80,000	Undetermined
H06172	1936	Undetermined	20,000	Undetermined
H06174	1936	Undetermined	20,000	Undetermined
H06154	1936	Undetermined	40,000	Undetermined
H06155	1936	Undetermined	40,000	Undetermined
H06156	1936	Undetermined	40,000	Undetermined
H06157	1936	Undetermined	40,000	Undetermined
H06173	1936	Undetermined	40,000	Undetermined
H06184	1936	Undetermined	80,000	Undetermined
H06185	1936	Undetermined	80,000	Undetermined
H06492	1939	Undetermined	20,000	Undetermined
H06513	1939	Undetermined	20,000	Undetermined
H06547	1940	Undetermined	160,000	Undetermined
H06548	1940	Undetermined	160,000	Undetermined
H06637	1940	Undetermined	20,000	Undetermined
H06638	1940	Undetermined	20,000	Undetermined
H06553	1940	Undetermined	40,000	Undetermined
H06549	1940	Undetermined	80,000	Undetermined
H06550	1940	Undetermined	80,000	Undetermined
H09789	1978	GCLWD	20,000	North American Datum 1927
H09832	1979	GCLWD	50,000	North American Datum 1927
B00133	1988	MLLW	50,000	North American Datum 1983
B00189	1989	MLLW	50,000	North American Datum 1983
B00190	1989	MLLW	50,000	North American Datum 1983
B00191	1989	MLLW	50,000	North American Datum 1983
B00197	1989	MLLW	50,000	North American Datum 1983
B00198	1989	MLLW	50,000	North American Datum 1983
B00199	1989	MLLW	50,000	North American Datum 1983
F00362	1992	Undetermined	20000	Undetermined
H10485	1993	MLLW	10000	North American Datum 1983
F00356	1993	Undetermined	10000	Undetermined
F00384	1993	Undetermined	10000	Undetermined
F00390	1993	Undetermined	10000	Undetermined

Table B-1: NOS Hydrographic datasets used in building the southern Louisiana DEMs

Survey ID	Year	Original Vertical Datum	Scale/Vertical Accuracy	Provided Horizontal Datum
F00391	1993	Undetermined	10000	Undetermined
F00393	1993	Undetermined	10000	Undetermined
F00397	1994	Undetermined	10000	Undetermined
F00398	1994	Undetermined	10000	Undetermined
F00401	1994	Undetermined	10000	Undetermined
H11179	2002	MLLW	20,000	North American Datum 1983
H11228	2003	MLLW	10,000	North American Datum 1983
H02715	Unkn	Undetermined	Undetermined	Undetermined

Table B-2: High Resolution hydrographic datasets in BAG format used in building the southern Louisiana DEMs

Survey ID	Year	Original Vertical Datum	Scale/Vertical Accuracy	Provided Horizontal Datum
D00140	2008	MLLW	Undetermined	North American Datum 1983
F00546	2007	MLLW	Undetermined	North American Datum 1983
H11683	2007	MLLW	Undetermined	North American Datum 1983
H11683	2007	MLLW	Undetermined	North American Datum 1983
H11683	2007	MLLW	Undetermined	North American Datum 1983
H11683	2007	MLLW	Undetermined	North American Datum 1983
H11684	2007	MLLW	Undetermined	North American Datum 1983
H11684	2007	MLLW	Undetermined	North American Datum 1983
H11684	2007	MLLW	Undetermined	North American Datum 1983
H11684	2007	MLLW	Undetermined	North American Datum 1983
H11834	2008	MLLW	Undetermined	North American Datum 1983
H11834	2008	MLLW	Undetermined	North American Datum 1983
H11834	2008	MLLW	Undetermined	North American Datum 1983
H11834	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983

Table B-2: High Resolution hydrographic datasets in BAG format used in building the southern Louisiana DEMs

Survey ID	Year	Original Vertical Datum	Scale/Vertical Accuracy	Provided Horizontal Datum
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983
H11836	2008	MLLW	Undetermined	North American Datum 1983

Table B-3: USACE hydrographic datasets used in building the southern Louisiana DEMs

Region	Year	Spatial Resolution	Original Vertical Datum	Provided Horizontal Datum
Mississippi River South and Southwest Pass	2010	∼50-300 m profile spacing ∼5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Mississippi River Gulf Outlet	2010	∼50-300 m profile spacing ∼5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Baptiste Collette Bayou	2009-2010	∼50-300 m profile spacing ∼5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Tiger Pass	2010	∼50-300 m profile spacing ∼5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Barataria Bay Waterway	2009-2010	∼50-300 m profile spacing ∼5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)

Table B-3: USACE hydrographic datasets used in building the southern Louisiana DEMs

Region	Year	Spatial Resolution	Original Vertical Datum	Provided Horizontal Datum
Bayou Laforche	2008-2010	~50-300 m profile spacing ~5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Houma Naviga-tional Channel	2010	~50-300 m profile spacing ~5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Atchafalaya River and Bay	2010	~50-300 m profile spacing ~5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)
Bayous Chene, Black and Boeuf	2010	~50-300 m profile spacing ~5-10 m point spacing	MLG (feet)	NAD 83 Louisiana State Plane (feet)

Table B-4: ENC datasets used in building the southern Louisiana DEMs

Chart	Title	Edition	Edition Date	Scale
US3GC03M	Mississippi River to Galveston	35.1	2010-09-07	1:458596
US3GC04M	Approaches to Mississippi River	42.2	2010-09-08	1:250000
US4LA25M	Isles Dernieres to Point au Fer	11.0	2010-06-21	1:80000
US4LA29M	Timbalier and Terrebonne Bays	11.1	2009-10-22	1:80000
US4LA30M	Mississippi River Delta;Southwest Pass;South Pass;Head of Passes	19.1	2010-06-23	1:80000
US4LA31M	Timbalier and Terrebonne Bays	22.1	2010-08-30	1:80000
US4LA32M	Barataria Bay and approaches	27.6	2010-06-22	1:80000
US4LA33M	Mississippi River Delta;Southwest Pass;South Pass;Head of Passes	21.1	2010-09-07	1:80000
US4LA34M	Chandeleur and Breton Sounds	22.1	2010-07-28	1:80000
US4LA35M	Mississippi River-Venice to New Orleans	31.2	2010-07-26	1:80000

Table B-4: ENC datasets used in building the southern Louisiana DEMs

Chart	Title	Edition	Edition Date	Scale
US5LA24M	Baptiste Collette Bayou to Mississippi River Gulf Outlet;Baptiste Collette Bayou Extension	34.0	2010-07-29	1:40000
US5LA26M	Port Fourchon and Approaches	17.5	2010-06-22	1:20000
US5LA36M	Intracoastal Waterway Waveland to Catahoula Bay	17.5	2010-02-03	1:40000
US5LA41M	Loop Deepwater Port Louisiana Offshore Oil Port	10.1	2010-04-26	1:50000